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A Study on Optimizing Hole Quality in Glass Fiber Composites through Parameter Analysis

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Abstract:
This study explores how cutting parameters impact the quality of drilled holes in glass fibre-reinforced thermoset polymers. Using Taguchi's L27 orthogonal array, the experiments were designed to optimise drilling parameters. Specifically, 6 mm twist drill bits were employed to drill holes at different feeds and spindle speeds. The analysis involved measuring maximum diameters on both the entry and exit sides of the drilled holes using an optical microscope to understand the influence of drilling parameters on machining damage.

Among the parameters tested, the study found that the smallest delaminated area on the front and back sides of the composite plate was achieved with the lowest feed rate (180 mm/rev) used in this study. Interestingly, even when the spindle speed was increased from 1700 rpm to 2400 rpm at a constant feed of 180 mm/rev, it reduced the maximum diameter on the front and back sides by 9 μm and 266 μm, respectively.

The findings suggest that optimizing drilling parameters can significantly increase material removal rates when working with glass fibre-reinforced thermoset polymers, all while maintaining or even enhancing hole quality without compromising structural integrity.

Background: *In the realm of composite materials, such as Glass Fiber Reinforced Polymer (GFRP), understanding and mitigating delamination is crucial. Delamination, the separation of layers, can significantly impact the structural integrity of composites. This study delves into the intricate details of delamination in GFRP, employing drilling as a method of exploration. The research incorporates both experimental techniques and statistical analyses to comprehensively examine and comprehend the factors influencing delamination in GFRP composites.*

Materials and Methods: *The composite specimens utilized in this study were crafted through the compression molding technique. By combining ML 506 epoxy resin with unidirectional E-glass fibers, these specimens were meticulously manufactured to exacting standards. The process involved employing the hand lay-up method, ensuring precision in integrating ML 506 epoxy resin and unidirectional E-glass fibers. This meticulous approach was aimed at tailoring the properties of the composite specimens to meet the specific requirements essential for the subsequent drilling experiments. Such detailed craftsmanship guarantees the credibility and suitability of the materials selected for this study's purposes.*

Results: *The interplay among speed, feed rate, and the number of fiber layers significantly influences the delamination factor at the entry and exit points, as well as the thrust experienced during the drilling process. Identifying optimal combinations of these parameters holds immense importance in reducing delamination and managing thrust, thereby enhancing both the efficiency and quality of drilling operations in composite materials.*

Conclusion: *This investigation not only expands our comprehension of drilling procedures in composite materials but also offers practical implications. The results underscore the significance of customized parameter choices to reduce delamination, fine-tune thrust, and elevate the overall quality and strength of drilled composite structures. Looking ahead, these revelations will act as a cornerstone for refining drilling techniques and propelling advancements in the realm of composite material manufacturing.*

Key Word: *Drilling, Composite, Hole Quality, Glass Fiber, Delamination*

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I. Introduction

In recent times, composite structures have gained immense traction in the aerospace industry owing to their advantageous traits, such as high specific strength, specific modulus, and cost-effectiveness when compared to metallic counterparts. Despite utilizing molding techniques to create near-perfect composite structures, additional processes like drilling remain essential for assembly using rivets and bolts. However, drilling in composite structures is intricate and demands meticulous attention to ensure precise hole quality and dimensions.

Holes in composite parts must be free from drilling-induced delamination and micro-cracks to uphold optimal tensile and fatigue strength in assemblies. Excessive delamination can significantly reduce the fatigue life of components, leading to sudden failure.

Numerous studies have delved into machining glass fiber-reinforced polymers (GFRPs), exploring factors like feed rates, spindle speeds, drill sizes, and fiber volume fractions and their impact on thrust force and torque during the drilling process. Some findings indicate that increasing feed rates, drill sizes, and fiber volume fractions can amplify thrust force and torque. Moreover, investigations into cryogenic and dry drilling techniques using TiAlN-coated carbide drill bits have yielded varying results. While cryogenic drilling didn't enhance hole quality for GFRPs, it showcased improved performance for carbon fiber-reinforced polymers (CFRPs) in other studies.

The wear and tear on tools due to repeated drilling operations have been thoroughly examined, revealing a correlation between tool wear and the number of machined holes. Strategies like applying vibration during drilling have shown promise in extending the critical number of holes before severe wear occurs. Studies monitoring the impact of drilling-induced damage on the tensile strength of unidirectional GFRPs have observed a reduction in strength corresponding to the extent of drilling-induced damage.

Significantly, investigations comparing uncoated and TiAlN-coated twist drill bits in drilling multidirectional and thick glass/epoxy composites found that the uncoated tool surpassed the coated one in terms of both delamination and tool wear. Considering that a single jet engine aircraft can contain up to 100,000 holes for fasteners and a commercial passenger transport aircraft can house up to 1,000,000 holes, ensuring the integrity of drilled parts becomes vital for safe aircraft operation.

This particular study evaluated the drilling performance of aerospace-grade GFRP using HSS twist drill bits under various machining parameters. The assessment of feeds and spindle speeds' influence on drilled hole quality was conducted by measuring delamination factors with an optical microscope. Taguchi and regression analyses were employed to identify the least significant parameter affecting the size of the delaminated area around the hole during drilling. Additionally, this paper offers expressions for calculating delamination factors on both the front and back sides of glass fiber-reinforced thermoset polymers based on spindle speeds and feeds.

II. Material And Methods

Composite Specimen Fabrication:

This study utilized a 3 mm thick unidirectional glass fiber reinforced epoxy plate with eleven, thirteen and fifteen layers of glass fiber to investigate drilling parameters and determine optimal machining conditions. The composite plate, having a rectangle shape with 250 mm X 30mm sides, underwent tests assessing tensile strength, tensile elastic modulus, flexure strength, density, and volume fraction according to industry standards (ASM D 3039, ASTM D 790, ASTM D 792, ASTM D 2734) as outlined in Table 1

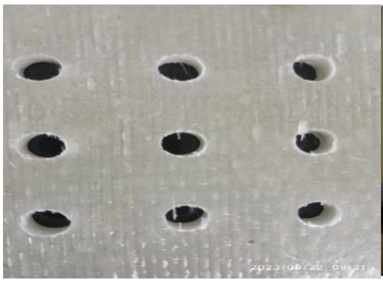


Figure:1. Glass fiber epoxy specimen

Figure2&3Vertical CNC Drilling machine

Drilling of GFRP materials:

Drilling tests were conducted on a CNC vertical milling machine (SMT VL 850) under dry-cutting conditions. To ensure perpendicular hole drilling on the composite surface, a wooden plate was affixed to the mill's table and levelled using an indexable end mill. Due to the challenges posed by large and non-planar aerospace composite structures, 6 mm diameter holes were drilled on the wooden plate to provide uniform support for the backside of the composite during drilling.

Securing the glass fiber composite onto the pre-machined wooden plates with M8 Socket head cap screws and washers ensured stable drilling operations and prevented workpiece movement-induced damage.

High-speed steel twist drills (EVAR DIN 338/R-N) with a 6 mm diameter, featuring a 118-degree point angle and 30-degree helix angle, were used in all machining tests. Three levels of rotational speed and feed were determined based on literature and initial observations, listed in Table 2, to study their effects on machining-induced damages.

A full factorial design using Taguchi's L9 orthogonal array was chosen to comprehensively analyze the impact of cutting parameters on final hole dimensions. Table 3 presents the rotational drilling speeds, feeds, and calculated material removal rates for each cutting set using the formula:

$MRR = \pi Dt^2 Nf/4$………………. (1)

Where Dt represents the drill bit diameter, N denotes spindle speed, and f signifies feed. Higher material removal rates were targeted to enhance machining efficiency while minimizing hole damage. To avoid the influence of tool wear on hole damage, a new tool was used for each cutting set, and experiments were repeated seven times to establish consistent trends in the results.

Delamination, a critical issue in composite drilling, arises from factors like fiber pull-out, fibre-matrix debonding due to thrust forces, and thermal damage. A delamination factor was defined to assess damage size based on the maximum diameter, calculated as the ratio of maximum diameter to nominal diameter, as illustrated in Figure 2. The composite plate was drilled using parameters from Table 3, and optical motorized microscopy (Zeiss AXIO Imager.M2m) was employed to measure the maximum diameters on the front and back sides of the holes. All findings will be discussed in subsequent sections.

The process initiates with a meticulous selection of materials. For this study, the chosen composite specimens are fabricated using the hand lay-up method.Two primary materials are carefully chosen:ML 506 Epoxy Resin: Selected for its documented performance and compatibility . Unidirectional E-Glass Fibers: Chosen for their reinforcing properties.

Configuration of Experimental Setup and Machining Parameters:

To craft the GFRP specimens, a high-strength E-glass chopped fiber mat was utilized as the reinforcement, combined with polyester resin. The resulting laminate slabs were tailored to measure 100 mm × 100 mm × 3 mm. The E-glass within the fiber mat boasted a modulus of 72.5 GPa and a density of 2590 kg/m³. Meanwhile, the chosen polyester resin exhibited a modulus of 3.25 GPa and a density of 1350 kg/m³.

The specimens were meticulously fashioned through a contact molding process. This involved stacking the necessary number of fiber mats to attain the desired thickness and achieve the target fiber volume fraction. The final fiber volume fraction, evaluated via the weight loss method, was determined to be 0.60.

To create the GFRP specimens, a high-strength E-glass chopped fiber mat was employed as the reinforcement material in combination with polyester resin. The resulting laminate slabs were designed to have dimensions of 100 mm × 100 mmX3. The E-glass used in the fiber mat had a modulus of 72.5 GPa and a density of 2590 kg/m3. The polyester resin chosen for this process possessed a modulus of 3.25 GPa and a density of 1350 kg/m3. The specimens were prepared using a contact molding process, where the required numbers of fiber mats were stacked to achieve the desired thickness and fiber volume fraction. The final fiber volume fraction was determined to be 0.60 using the weight loss method.

Drilling set-up:

Dry drilling experiments were performed using 6mm diameter carbide-coated drill bits on a CNC TRIAC VMC machining center from Denford, UK. The setup included a force-torque strain gauge drilling dynamometer, fixture, amplifier, connecting cables, an A/D converter, and a PC for data collection.

A rigid fixture attached the laminate composite specimen to the dynamometer, which was in turn mounted on the machine table. The experimental arrangement is depicted in Figures 2 and 3 schematically.

Table 1 Levels of the variables used in the experiment.

Sr no	Level1	Level2	Level3
	Cutting Speed in rpm	No.of layers	Feed rate in mm/min
1	1700	11	180
2	2100	13	230
3	2400	15	280

These levels represent the specific settings or values chosen for each variable in the experiment. For instance, the cutting speed (revolutions per minute - rpm), the number of layers of the composite material, and the feed rate (how fast the drill advances into the material) were varied at different levels to observe their impact on the drilling process and the resultant hole characteristics. Each level represents a distinct parameter setting tested during the experiment to evaluate their effects on drilling performance.

Experimental Design

Design of experiments is a robust analytical tool employed to comprehend how different process variables influence a particular outcome, often an unknown function of these variables. Key to this process is selecting control factors. It's recommended to incorporate numerous process variables to pinpoint the most impactful ones early on. In our experiment, we utilized a full factorial design featuring four factors, each spanning four levels, as detailed in Table 1. It's essential to highlight that our primary emphasis isn't an exhaustive analysis of the variability linked to these parameters.

The Taguchi Method

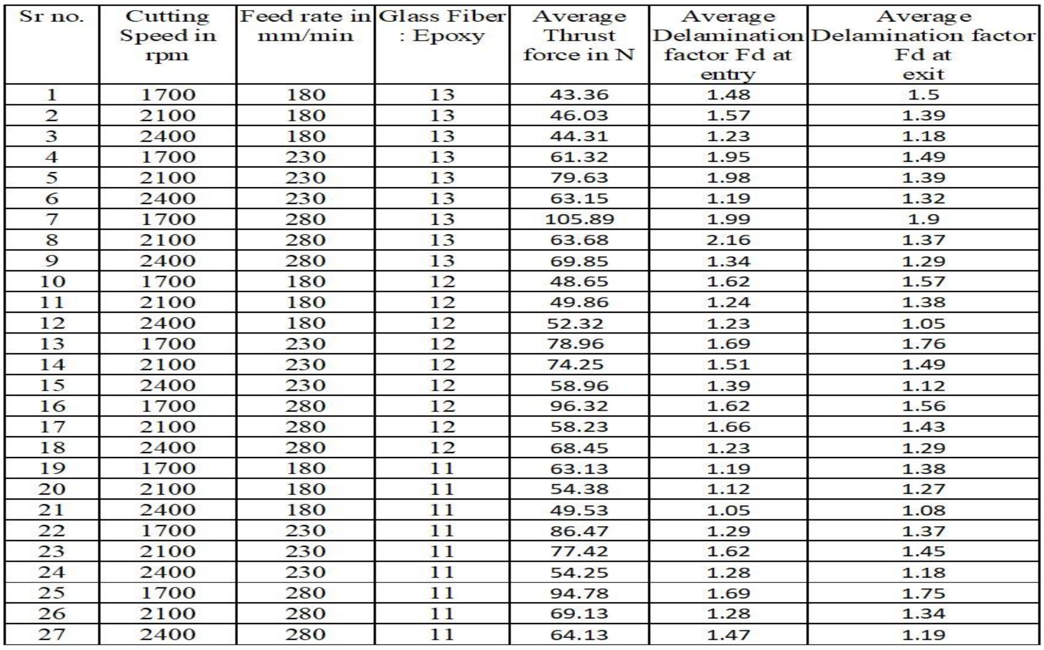
Robust design in engineering aims to secure product and process conditions that remain resilient against varied sources of variation. Its goal is to deliver high-quality products while curbing development and manufacturing expenses. Taguchi's parameter design, integral to robust design, presents a systematic strategy for optimizing performance, quality, and cost. It amalgamates experimental design theory with the concept of the quality loss function, offering solutions to intricate manufacturing dilemmas.

To gauge the impact of control factors (feed rate, spindle speed, drill diameter, and workpiece thickness) in drilling, we employed a full factorial design encompassing four factors, each with four levels. Taguchi defines product quality in terms of the loss inflicted on society from product shipment to the customer. These losses can stem from deviations in a product's functional characteristics, termed losses due to functional variation. Noise factors, uncontrollable elements causing functional deviations, encompass external factors like temperature and human elements. Quality engineering aims to fortify products against all noise factors.

The Taguchi method harnesses special orthogonal arrays to traverse the entire parameter space with minimal experiments. The outcomes are then translated into a signal-to-noise (S/N) ratio. Taguchi advocates employing the S/N ratio to gauge the deviation of quality characteristics from desired values. A higher S/N ratio denotes superior quality characteristics. Consequently, optimal process parameter levels correspond to the highest S/N ratio. Furthermore, statistical analysis of variance (ANOVA) pinpoints statistically significant process parameters. The ideal combination of process parameters is forecasted using S/N and ANOVA analyses. Subsequently, a confirmation experiment validates the optimal process parameters derived from the parametric design.

The Taguchi method furnishes a methodical and efficient approach for optimizing process parameters, centering on the use of S/N ratio and ANOVA analyses. The final confirmation experiment assures the practical application and reliability of the identified optimal process parameters.

Table 2 Observation table



Sr no.	Cutting Speed in rpm	Feed rate in mm/min	Glass Fiber : Epoxy	Average Thrust force in N	Average Delamination factor Fd at entry	Average Delamination factor Fd at exit
1	1700	180	13	43.36	1.48	1.5
2	2100	180	13	46.03	1.57	1.39
3	2400	180	13	44.31	1.23	1.18
4	1700	230	13	61.32	1.95	1.49
5	2100	230	13	79.63	1.98	1.39
6	2400	230	13	63.15	1.19	1.32
7	1700	280	13	105.89	1.99	1.9
8	2100	280	13	63.68	2.16	1.37
9	2400	280	13	69.85	1.34	1.29
10	1700	180	12	48.65	1.62	1.57
11	2100	180	12	49.86	1.24	1.38
12	2400	180	12	52.32	1.23	1.05
13	1700	230	12	78.96	1.69	1.76
14	2100	230	12	74.25	1.51	1.49
15	2400	230	12	58.96	1.39	1.12
16	1700	280	12	96.32	1.62	1.56
17	2100	280	12	58.23	1.66	1.43
18	2400	280	12	68.45	1.23	1.29
19	1700	180	11	63.13	1.19	1.38
20	2100	180	11	54.38	1.12	1.27
21	2400	180	11	49.53	1.05	1.08
22	1700	230	11	86.47	1.29	1.37
23	2100	230	11	77.42	1.62	1.45
24	2400	230	11	54.25	1.28	1.18
25	1700	280	11	94.78	1.69	1.75
26	2100	280	11	69.13	1.28	1.34
27	2400	280	11	64.13	1.47	1.19

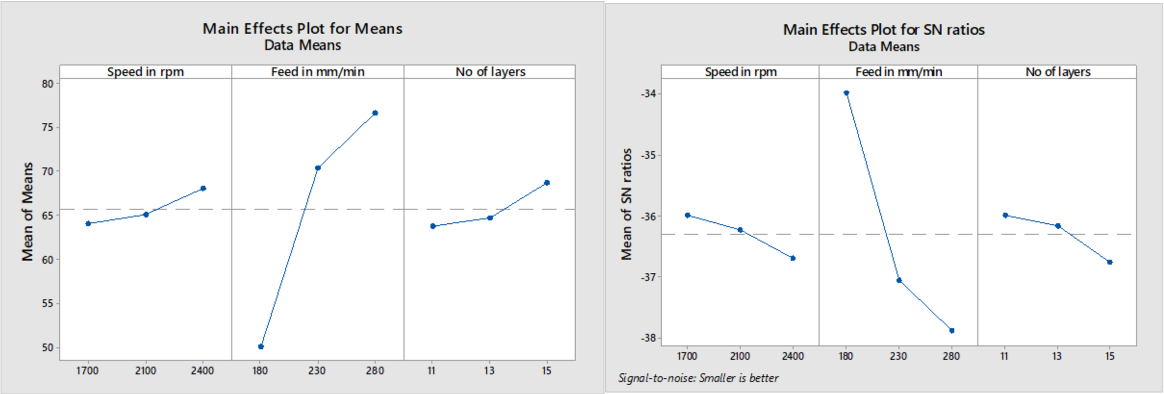


Figure 5: Main effects plots for minimizing Thrust.

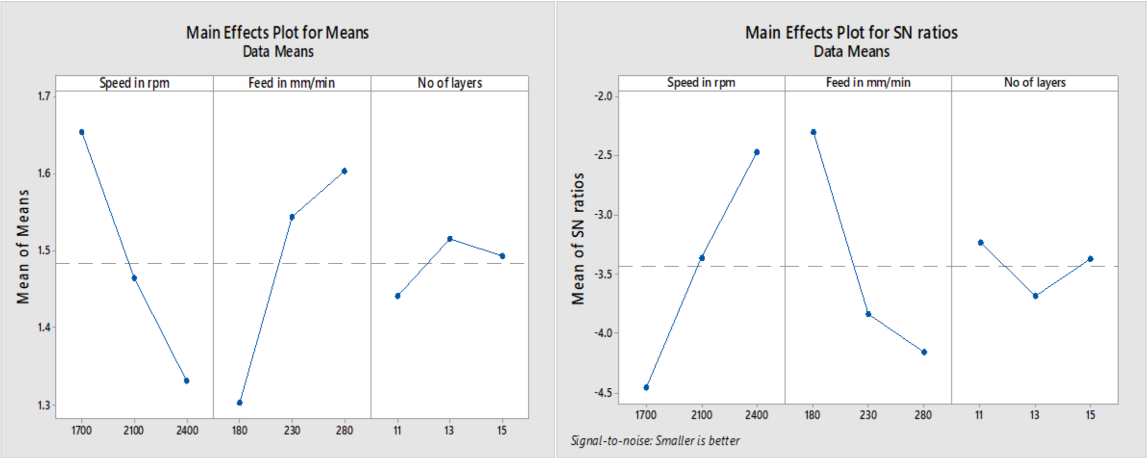


Figure 6: Main effects plots for minimizing delamination at entry.

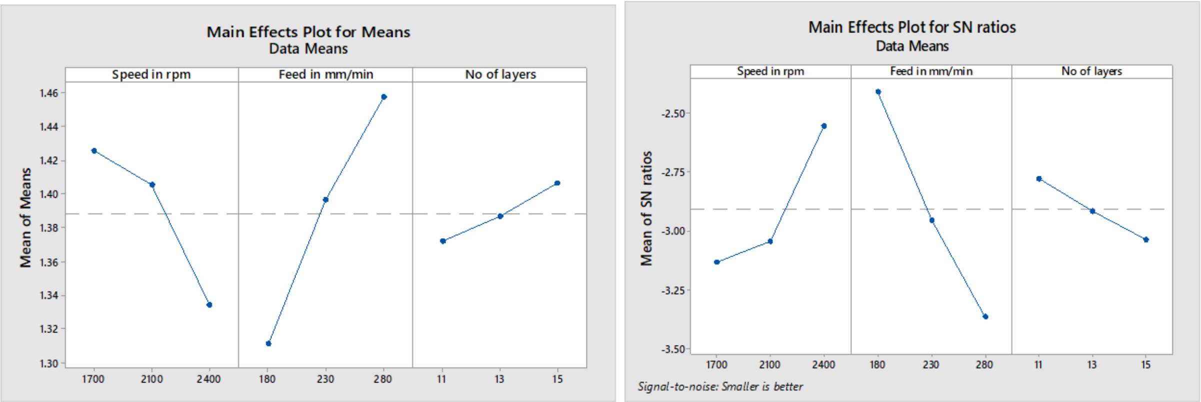
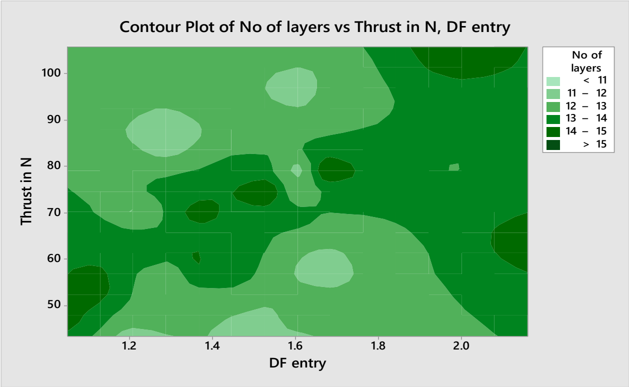
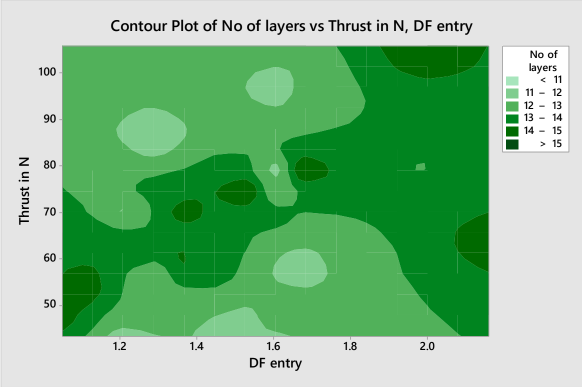
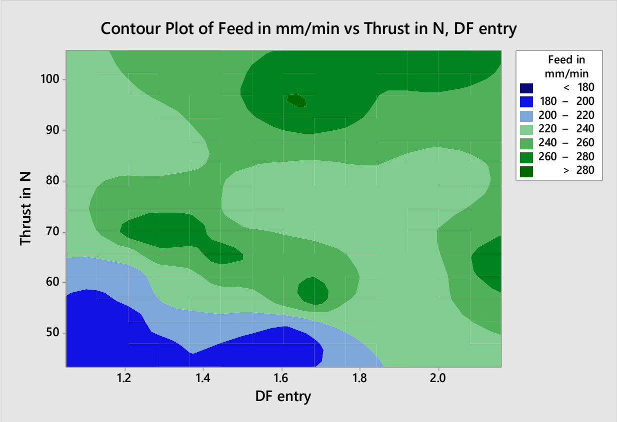


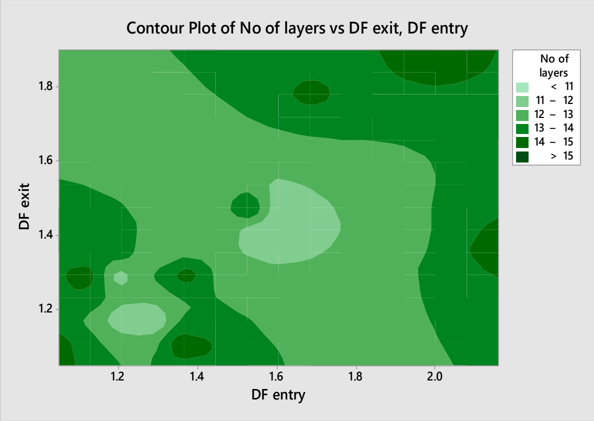
Figure 7: Main effects plots for minimizing delamination at exit.

Figures 5,6 & 7 explain as Main effects plots for minimizing Thrust, delamination at entry and exit" is a visual tool that provides a comprehensive overview of how variations in speed, feed, and the number of fiber layers influence the critical factors of thrust and delamination at entry and exit points in the drilling process.


Contour Plot of No of layers vs Thrust in N, DF entry
Thrust in N
100
90
80
70
60
50
1.2
1.4
1.6
1.8
2.0
DF entry
No of layers
< 11
11 – 12
12 – 13
13 – 14
14 – 15
> 15


Contour Plot of No of layers vs Thrust in N, DF entry
Thrust in N
100
90
80
70
60
50
1.2
1.4
1.6
1.8
2.0
DF entry
No of layers
< 11
11 – 12
12 – 13
13 – 14
14 – 15
> 15


Contour Plot of Feed in mm/min vs Thrust in N, DF entry
Thrust in N
100
90
80
70
60
50
1.2
1.4
1.6
1.8
2.0
DF entry
Feed in mm/min
< 180
180 – 200
200 – 220
220 – 240
240 – 260
260 – 280
> 280


Contour Plot of No of layers vs DF exit, DF entry
DF exit
1.8
1.6
1.4
1.2
1.2
1.4
1.6
1.8
2.0
DF entry
No of layers
< 11
11 – 12
12 – 13
13 – 14
14 – 15
> 15

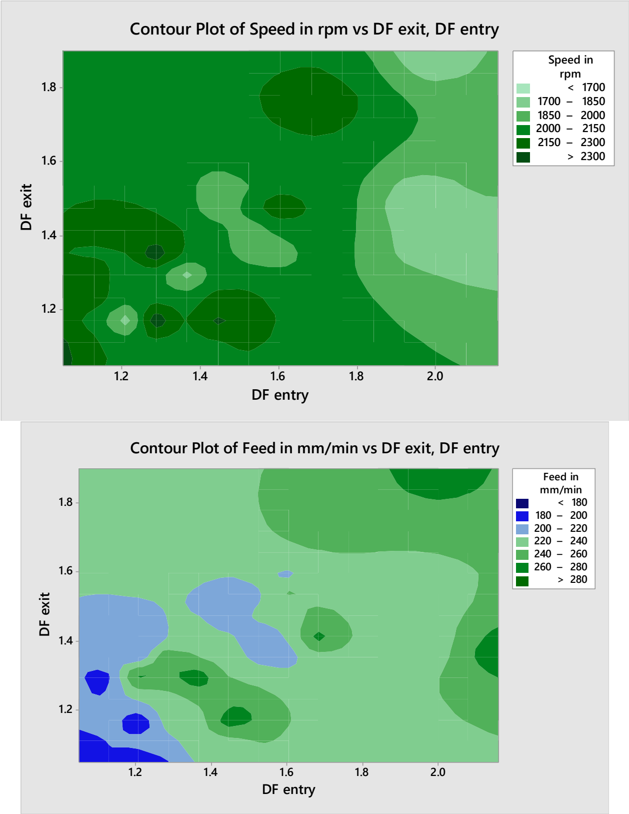


Figure 8: Contour plots for minimizing Thrust, delamination at entry and exit.

Figure 8, Contour plots for minimizing Thrust and delamination at entry and exit, serves as a visual representation to comprehend the intricate relationships among multiple factors and their collective impact on thrust and delamination during the drilling process of composite materials.

The input parameters, consisting of speed, feed, and the number of layers, are vital variables that researchers and practitioners can manipulate or control during the drilling operation. These parameters significantly influence the drilling process in composite materials.

The output parameters, namely thrust and delamination at entry and exit points, depict the consequences or results of the drilling process. Thrust represents the force applied during drilling, while delamination at entry and exit points signifies the occurrence of damage or separation of layers in the composite material around the drilled hole.

The contour plots offer a graphical depiction of how variations in the input parameters (speed, feed, number of layers) impact the output parameters (thrust, delamination). By observing these plots, one can visualize how changes in the input parameters influence the thrust force applied and the extent of delamination at the entry and exit points of the drilled holes.

III. Result

Optimal Settings for Optimization:

Speed: 2400 rpm
Feed: 180 mm/min
Number of Layers: 11

Fig.9.explain as The provided optimal settings for optimization—2400 rpm for speed, 180 mm/min for feed, and 11 layers for the number of layers—represent the specific parameter values that are deemed most effective in achieving particular objectives in the context of the drilling process for composite materials.

Speed (2400 rpm):

This setting refers to the rotational speed of the drilling tool. Optimal performance was observed at 2400 revolutions per minute (rpm), indicating that at this speed, the drilling operation produced the desired outcomes, possibly by minimizing certain undesired effects like excessive heat generation or tool wear, while effectively completing the drilling process within the composite material.

Feed (180 mm/min):

The feed setting, indicating the rate at which the drill advances into the material, was found optimal at 180 mm/min. This rate likely facilitated the drilling process, balancing the pace of the drill's penetration into the composite material without causing significant damage or delamination around the hole.

Number of Layers (11):

The ideal number of layers, set at 11, signifies the quantity of composite layers within the material. This specific configuration was identified as optimal, likely because it provided the necessary structural integrity while minimizing the potential for delamination or damage around the drilled hole.

These optimal settings are derived from the study's objectives of achieving efficient drilling with minimal thrust, reduced delamination at entry and exit points, and maintaining high-quality hole characteristics in composite materials. They represent a balanced combination of parameters that collectively contribute to achieving the desired outcomes in the drilling process while mitigating adverse effects or damage to the material structure.

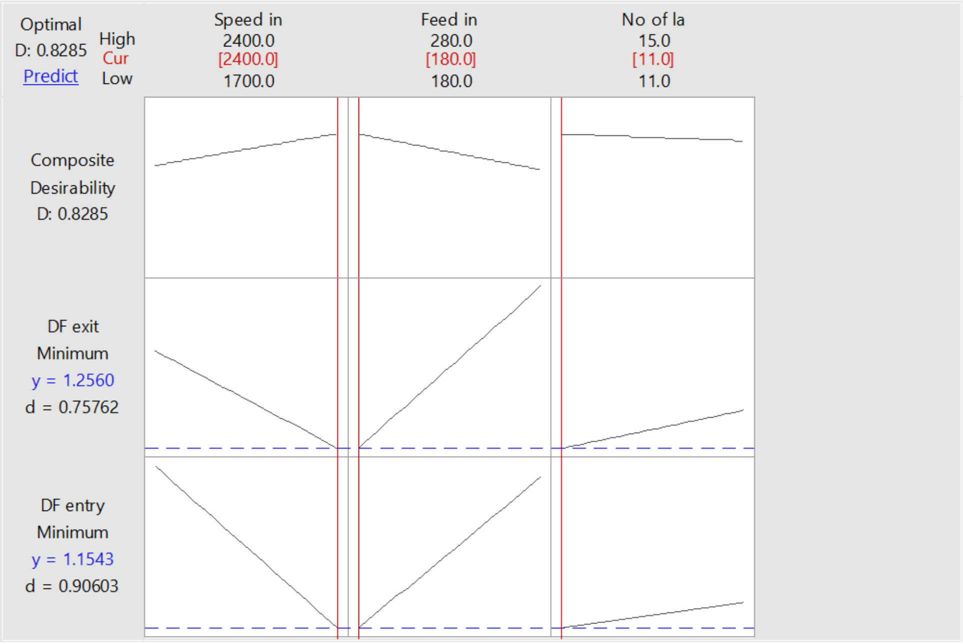


Figure 9. Optimization plot

IV. Discussion

These identified optimal settings align with the objectives of the study, aiming to achieve efficient drilling while minimizing undesirable outcomes such as thrust, delamination at entry and exit points, and maintaining high-quality hole characteristics. They represent a refined combination of parameters that collectively contribute to an optimized drilling process for composite materials, ensuring both effective hole creation and reduced potential for structural damage or defects.

V.Conclusion

The culmination of identifying optimal settings—2400 rpm for speed, 180 mm/min for feed, and 11 layers for the number of composite layers—reflects a significant achievement in optimizing the drilling process for composite materials.

Through meticulous experimentation and analysis, these specific parameter configurations have been pinpointed as the most effective in achieving the study's objectives. The quest for optimized drilling aimed to reduce thrust, minimize delamination at entry and exit points, and uphold high-quality hole characteristics within composite materials.

The chosen speed of 2400 rpm demonstrates an optimal rotational velocity for the drilling tool, balancing efficiency with the avoidance of detrimental effects like excessive heat or tool wear. Similarly, the feed rate of 180 mm/min represents an optimal pace of drill advancement, ensuring controlled penetration without compromising the material's integrity.

Furthermore, the selection of 11 layers for the composite material strikes a balance between structural support and mitigating potential damage during drilling. This configuration likely provides ample stability without inducing significant delamination or structural flaws around the drilled holes.

Ultimately, these optimized settings underscore a careful equilibrium achieved in the drilling process. They signify a balance between achieving the desired outcomes—efficient drilling with minimal damage or defects—and maintaining the structural integrity of the composite material. This conclusion solidifies the importance of meticulous parameter selection in achieving superior drilling results within composite material fabrication.

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